Method for Treatment of Severe Acute Respiratory Syndrome (SARS) using Triptolide Derivatives and Prodrugs

Background of the Invention

SARS

Severe Acute Respiratory Syndrome (SARS) is a serious public health threat. Although identification and isolation of infected individuals contributes to limitation of the spread of SARS infection, periodic renewed outbreaks and reemergence of the infection in patients previously thought to have recovered from SARS indicate the ongoing unmet need for improved therapy for SARS.

SARS is caused by a coronavirus (the SARS coronavirus, or SARS-CoV) and is a serious, contagious, rapidly progressing disease. The life-threatening aspect of SARS involves the lungs, and appears to result from a progression of pulmonary disease involving diffuse alveolar damage, a fibrosis-like condition in the lungs, and acute respiratory distress. There is evidence that the viral content in the lungs of SARS patients peaks and begins decreasing before the clinical severity of SARS symptoms reaches a peak. Based on the experience in Hong Kong, the SARS clinical course has been divided into three phases: the viral replicative phase, the immune hyperactive phase, and the lung destructive phase.

Changes in lung tissue indicate that cytokine production is involved in the pathologic effects upon the lungs (1). In acute viral respiratory infections, early-response cytokines such as IFN-γ, TNF-α, IL-1β and IL-6 mediate lung injury (2). Respiratory viruses, particularly certain types of influenza virus, are potent inducers of proinflammatory cytokines and produce cytokine disregulation, which contributes to the pathogenesis and unusual severity of some human influenza viral infections (3). Patients with the highly virulent 1997 avian flu had primary viral pneumonia complicated by acute respiratory distress, a syndrome that is associated with cytokine disregulation (4).

The reduction of virus (SARS-CoV) content before the peak of the disease process and the usefulness of corticosteroid treatment, as noted below, suggest that the development of the most severe, life-threatening effects of SARS may result from the exaggerated response of the body to the infection (immune hyperactivity) rather than effects of the virus itself. Corticosteroid treatment is used in SARS patients to suppress the massive release of cytokines that may characterize the immune hyperactive phase, in the hope that it will stop the progression of pulmonary disease in the next phase.

Corticosteroid treatment has produced good clinical results. In many cases, lung shadows on X-rays start to resolve, and oxygenation improves after corticosteroid treatment. The majority of SARS patients receiving corticosteroid therapy in one clinic

responded with resolution of fever and lung opacities within two weeks. Hydrocortisone or prednisolone has become first-line therapy, and a 2-day i.v. course of methylprednisolone is used in the most severe cases in most patients.

Although corticosteroids appear to reduce some of the major symptoms of SARS, there are several treatment-related side effects, and there is a clear need for more selective agents.

Triptolide as an Immunosuppressive Agent

The compound triptolide, a diterpene triepoxide isolated from the Chinese medicinal plant *Tripterygium wilfordii*, has potent immunosuppressive and antiinflammatory properties and reduces T lymphocyte proliferation and recruitment (5). The compound suppresses in vitro production of proinflammatory cytokines such as IFN-γ, TNF-α, IL-1β and IL-6, as shown in Table 1.

To obtain the data, Jurkat cells were stimulated for 8 hr by PMA and ionomycin. Human peripheral blood mononuclear cells (PBMC) from a single donor were incubated for 24 hr with PHA. At the end of the culture period, each supernatant was harvested, and the cytokine content was assayed by ELISA.

Table 1. Suppression of cytokine production by triptolide

Cells and stimulus	Cytokine	IC_{50} (ng/ml)
PMA/ionomycin-induced Jurkat cells	IL-2	1.3
PHA-induced PBMC	IL-1β	0.45
	IL-2	0.38
	IL-6	1.5
	TNF-α	0.35
	IFN-γ	0.52

Triptolide suppresses the production of cytokines in a variety of *in vitro* systems. For example, triptolide inhibits early cytokine gene expression in Jurkat T cells, effectively suppressing T lymphocyte activation (5). Triptolide inhibits production of IL-2 in activated human peripheral blood mononuclear cells (PBMC) and in activated Jurkat cells (Table 1; refs 5 and 11). The secretion of the proinflammatory cytokines IFN-γ, TNF-α, IL-1β and IL-6 by PHA-activated human PBMC is also suppressed by triptolide (Table 1). Triptolide inhibits the expression of several cytokine genes in activated Jurkat cells, including IL-2, IL-3, IL-6, IL-8, IL-13, TNF-α, TGF-β, MIP-1α, MIP-1β, GM-CSF and RANTES (11). In addition to its effects on immune cells,

triptolide suppresses IL-8 expression by bronchial epithelial cells, inhibiting both IL-8 mRNA and IL-8 protein expression (5).

Description of the Invention

In accordance with the present invention, triptolide prodrugs and derivatives are effective to inhibit cytokine production and are thus useful in the treatment of SARS, alone or in combination with other immunosuppressive agents.

Such triptolide derivatives and prodrugs have been described in several co-owned US patents, including U.S. Patent Nos. 5,663,335, 6,150,539, 6,458,537, and 6,569,893, each of which is hereby incorporated by reference in its entirety. The derivatives can be prepared, as described therein, from triptolide, a plant-derived diterpene triepoxide that suppresses in vitro production of proinflammatory cytokines such as IFN-γ, TNF-α, IL-1β and IL-6.

An exemplary triptolide derivative, triptolide 14-succinate (designated PG490-88; see U.S. Patent No. 5,663,335), is converted *in vivo* to triptolide by the action of esterases in plasma, and has shown efficacy in several animal models of immunosuppression (6-9). The compound has shown *in vitro* activity in suppression of IL-2 production after incubation in plasma, and was effective in an animal model (bleomycin model) of lung fibrosis, markedly reducing the number of myofibroblasts in the bleomycin treatment group (10). The compound also produced a significant decrease in the level of TGF-β in the bronchoalveolar lavage fluid, and blocked the bleomycin-induced increase in TGF-β mRNA in cultured normal human lung fibroblasts.

Fibrosis usually develops in a chronic manner, and fibrosis has been seen after recovery in a small percentage of SARS patients (1). A triptolide prodrug or derivative is expected to prevent the development of fibrotic sequelae in SARS, as well as non-fibrosis-related lung pathology resulting from cytokine production and the cytokine-induced effects upon lung tissue, aspects of SARS that are more acute and life threatening than fibrosis.

Further exemplary triptolide derivatives and prodrugs include 14-methyltriptolide (designated PG670; see US provisional application serial no. 60/434,203), triptolide 14-tert-butyl carbonate (designated PG695; see US provisional application serial no. 60/384,480), 14-deoxy-14α-fluoro triptolide (designated PG763; see US provisional application serial no. 60/449,976) and triptolide 14-(α-dimethylamino)acetate (designated PG702; see U.S. Patent No. 5,663,335). Each of these US applications is hereby incorporated by reference in its entirety. Many of these compounds are believed to act as prodrugs, by converting *in vivo* to triptolide, as observed for PG490-88, above. Others, such as 14-deoxy-14α-fluoro triptolide, are not expected to undergo such

conversion, but nonetheless exhibit biological activities shown by triptolide (e.g. cytotoxicity in human T cell lymphoma (Jurkat) cells and inhibition of IL-2), as reported in US application serial no. 449,976, cited above.

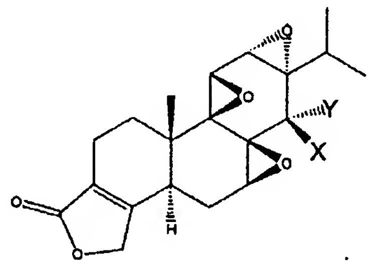

Table 2. Exemplary Triptolide Derivatives and Prodrugs

	X	Y
PG490-88	$-O(CO)CH_2CH_2COOH$	-H
PG670	-OH	$-CH_3$
PG695	$-O(CO)OC(CH_3)_3$	-H
PG702	$-O(CO)CH_2N(CH_3)_2$	-H
PG673	-H	-F

Triptolide derivatives and prodrugs useful in the invention are not limited to the exemplary compounds shown herein. For further derivatives and prodrugs, see the U.S. patents and applications incorporated by reference herein.

As noted above, the triptolide derivatives and prodrugs can be used in combination with other immunosuppressive agents. Other compounds with immunosuppressive activity include, for example: azathioprine, brequinar, chlorambucil, 2-chloro deoxyadenosine, cyclosporin, cyclophosphamide, 15-deoxyspergualin, dexamethasone, everolimus, fluorouracil, leflunomide, mercaptopurine, methotrexate, mitomycin, mitoxantrone, mizoribine (bredinin), mycophenolate mofetil, prednisone, prednisolone, sirolimus (rapamycin), thalidomide, tacrolimus (fk506), thioguanine, and thiopurine).

The level of cytokines can also be reduced, and the morbidity and mortality of SARS reduced, by the use of biological agents that have specificity for any of the cytokines produced in a SARS infection or prevent binding of these cytokines to cytokine receptors on target cells. Cytokine antagonists comprised of soluble receptors, antibodies, or binding proteins for the cytokines, or receptors to the cytokines, produced in a SARS infection may contribute to reduction in the cytokine levels. Cytokines such as TNF-α, IL-1β, IL-6, IL-8, IL-18 and others may be involved in the pathogenesis of SARS, and cytokine antagonists that bind to these or other cytokines or their receptors may prevent their biological effects and thus reduce the morbidity and mortality of the

SARS infection. Etanercept™ (a soluble TNF receptor antagonist), Infliximab™ (an anti-TNF antibody) and Anakinra™ (a soluble IL-1 receptor antagonist) are examples of cytokine antagonists, and reagents targeting these and other cytokines/cytokine receptors are in preclinical and clinical development.

More than one of the cytokine antagonists described herein may be used in combination. The cytokine antagonists are specifically targeted at a single cytokine pathway. As it is likely that multiple cytokines are involved in the pathogenesis of SARS, it is possible that targeting a single cytokine may not sufficiently reduce the morbidity and mortality of SARS. Combination treatment with PG490 derivatives and prodrugs, immunosuppressive agents, and cytokine antagonists may be used to increase the effectiveness of the treatment.

<u>Virus Detection</u>

For practical reasons and based on evidence provided by the WHO (World Health Organization) laboratory network, upper respiratory specimens are most suitable for virus detection (isolation and RNA detection). Sampling from multiple sites increases detection rate. The polymerase chain reaction (PCR) can be used to detect genetic material of the SARS-CoV in various specimens (blood, stool, respiratory secretions or body tissues).

Antibody tests detect antibodies produced in response to SARS-CoV infection. Different types of antibodies (IgM and IgG) appear and change in level during the course of infection. They can be undetectable at the early stage of infection. IgG usually remains detectable after resolution of the illness. The following test formats are being developed:

• ELISA (Enzyme Linked ImmunoSorbant Assay): a test detecting a mixture of IgM and IgG antibodies in the serum of SARS patients yields positive results reliably at around day 21 after the onset of illness.

• IFA (Immunofluorescence Assay): a test detecting IgM antibodies in serum of SARS patients yields positive results after about day 10 of illness. This test format is also used to test for IgG. This is a reliable test requiring the use of fixed SARS-CoV and an immunofluorescence microscope.

Virus in specimens (such as respiratory secretions, blood or stool) from SARS patients can also be detected by inoculating cell cultures and growing the virus. Once isolated, the virus must be identified as the SARS virus with further tests. Cell culture is a very demanding test, but is currently (with the exception of animal trials) the only means to show the existence of live virus.

Clinical experience in the Toronto, Canada SARS outbreak indicates that, in a small

sample, ribavarin and steroids did not appear to affect viral load. It is widely thought that ribavarin has little if any effect upon SARS, based partially on the lack of *in vitro* activity in production of the SARS CoV in tissue culture cells. However, the corticosteroid dose used in Toronto is lower than that used in Hong Kong clinical practice. Nonetheless, monitoring of the viral level in the lungs is advisable when practicing this invention.

Timing of treatment

Treatment with the triptolide prodrugs or derivatives and/or other immunosuppressive agents, as described in this invention, is initiated when the patient's clinical condition warrants intervention. It is important to follow the level of the SARS-CoV and to delay initiation of this treatment until the level of the SARS-CoV in the lungs has declined significantly from a peak level, so that the treatment does not compromise the immune capacity of the patient to the extent that the continued decline of the viral load is interrupted or compromised. Decline in the viral load indicates that the first phase of the disease has passed, and therapy to intervene in the development of the second phase is appropriate. Testing to determine the level of SARS-CoV is therefore advisable in making a decision on the initiation of treatment. Treatment continues until there is clear evidence of efficacy and the viral load has remained at a very low level. The pathology characteristic of SARS must be well controlled, and the viral load must not have increased again after falling from the peak level.

Route of treatment

Although more than a single route of administration will likely have a therapeutic effect, most patients infected with SARS-CoV and showing the appropriate symptoms to be classified as SARS patients will be in an acute care, in-patient setting. The patients will likely be receiving intravenous infusions/injections in their supportive care regimen. Under these circumstances, using the intravenous route for treatment according to this invention should be acceptable, and intravenous injection/infusion should be considered the preferred route of administration. Alternative routes of administration are not excluded, however.

Dose, Schedule and Duration of treatment

A range of doses is practical for this treatment. Results from a phase I clinical trial with a triptolide prodrug, triptolide succinate sodium salt (designated PG490-88Na), show that a dose of 0.675 $\mu g/m^2$ administered by i.v. infusion is well tolerated with no drug-related toxicity. This dose calculates to about 20 µg/kg. Treatment in this clinical study is administered at weekly intervals.

For administration to human patients, a reasonable range of doses, for a prodrug that converts to triptolide in human plasma at a rate similar to that of triptolide succinate, is 1 μg/kg to 100 μg/kg. For derivatives which do not require conversion for activity, such as 14-deoxy-14α-fluoro triptolide, a lower dose range will be useful, such as 0.1 to 40 μg/kg, depending upon the activity of the derivative compared to that of triptolide.

It is reasonable to treat SARS patients several times per day by i.v. infusion with the triptolide prodrugs or derivatives, or possibly by continuous infusion, as dictated by their clinical state and response to the treatment. With more frequent, or continuous treatment, the dose on a $\mu g/m^2$ or μg/kg basis would be reduced.

In addition, lymphopenia is seen in some SARS patients. It is important to avoid exacerbating or extending the period of lymphopenia by the treatment described herein. The lymphocyte level should be monitored, and the treatment dose should be adjusted accordingly to avoid treatment-related lymphopenia.

Immunity to SARS

The mechanism of immunity to SARS-CoV leading to recovery from SARS is unknown. It is unclear which arms of the immune system are involved in the response to SARS infection, and which immune responses contribute to overcoming the infection. The notion of immune hyperactivity has been reported, and the massive production of cytokines would be consistent with this. Cytokines are produced by cells of the immune system, as well as other cells in the body. Bronchial epithelial cells produce cytokines. Monocytes, macrophages, endothelial, and epithelial cells produce IL-1β. Immune cells, fibroblasts and lung epithelial cells produce IL-8. Monocytes, macrophages, lymphocytes produce TNF-α.

It is possible that the treatment described herein, involving inhibition of cytokine production, may, in some patients, have a negative impact upon the development and expression of immunity to SARS CoV. It is also possible that the treatment described in this invention may, in some patients, interrupt the decrease in viral level, or result in an increase in the viral level. It is thus advisable to monitor aspects of the immune system as well as the viral level to allow modulation of the treatment.

Combination treatment

In a rapidly progressing, life-threatening disease like SARS, combination or multiple treatment is the norm, particularly when the symptoms of the disease are being treated rather than the initial cause of the disease – the virus. The described triptolide derivatives and prodrugs may be in concert with other agents. These additional agents include, but are not limited to antiviral agents, corticosteroids, additional

immunosuppressive agents, e.g. as described above, and immune potentiators.

Repeat treatment

Evidence from other, non-SARS-related strains of human coronaviruses indicates that long-term, protective immunity does not develop, and the same person can be repeatedly infected with the same virus. If protective immunity does not develop with SARS, and reinfection can occur, then repeat treatment with the agents described in this invention may be necessary. The renewed use of this treatment would not be expected to be problematic.

Evidence of efficacy

The main evidence for the efficacy of the treatment approach described here is recovery of SARS patients from the disease, and recovery without the serious sequelae associated with SARS infection. The particular cytokine(s) responsible for the lung pathophysiology observed in SARS have not been identified. It is likely that a combination of cytokines is involved. Evaluation of the level of several individual cytokines in bronchoalveolar lavage fluid and or patient plasma may give an indication of the progression of the response to SARS viral infection and of the efficacy of the treatment.

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Triptolide Lactone Ring Derivatives as Immunomodulators and Anticancer Agents

Field of the Invention

The present invention relates to compounds useful as immunosuppressive, anti-inflammatory and anticancer agents.

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Background of the Invention

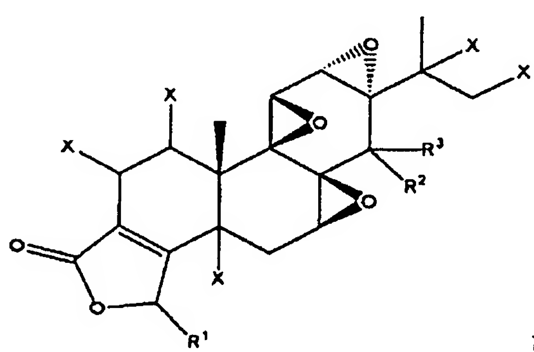
Immunosuppressive agents are widely used in the treatment of autoimmune disease and in treating or preventing transplantation rejection, including the treatment of graft-versus-host disease (GVHD). Common immunosuppressive agents include azathioprine, corticosteroids, cyclophosphamide, methotrexate, 6-mercaptopurine, vincristine, and cyclosporin A. In general, none of these drugs are completely effective, and most are limited by severe toxicity. For example, cyclosporin A, a widely used agent, is significantly toxic to the kidney. In addition, doses needed for effective treatment may increase the patient's susceptibility to infection by a variety of opportunistic invaders.

The compound triptolide, obtained from the Chinese medicinal plant *Tripterygium wilfordii* (TW), and certain derivatives and prodrugs thereof, have been identified as having immunosuppressive activity, *e.g.* in the treatment of autoimmune disease, and in treating or preventing transplantation rejection, including the treatment of graft-versus-host disease (GVHD). See, for example, co-owned U.S. Patent Nos. 5,962,516 (Immunosuppressive compounds and methods), 5,843,452 (Immunotherapy composition and method), 5,759,550 (Method for suppressing xenograft rejection), 5,663,335 (Immunosuppressive compounds and methods), 5,648,376 (Immunosuppressant diterpene compound), and 6,150,539 (Triptolide prodrugs having high aqueous solubility), which are incorporated by reference. Triptolide and certain derivatives and prodrugs thereof have also been reported to show anticancer activity; see, for example, Kupchan *et al.*, 1972, 1977, as well as co-owned U.S. Patent No. 6,620,843 (Sep 2003), which is hereby incorporated by reference.

Although derivatives and prodrugs of triptolide have provided benefits relative to native triptolide in areas such as pharmacokinetics or biodistribution, *e.g.* by virtue of differences in lipid or aqueous solubility, or via their activity as prodrugs, the biological activity per se of triptolide derivatives is often significantly less than that of native triptolide.

Summary of the Invention

In one aspect, the invention provides compounds which are useful for immunosuppressive, anti-inflammatory and anticancer therapy. The compounds are derivatives of triptolide represented by formula I:



I

where

R^1 is alkyl, alkenyl, alkynyl, arylalkyl, aryl, arylacyl, or $C(OH)R^4R^5$,

wherein R^4 and R^5 are independently hydrogen, alkyl, cycloalkyl, alkenyl, cycloalkenyl, any of which, excepting hydrogen, may be substituted with alkoxy, hydroxy, acyloxy, or aryl;

CR^2R^3 is CHOH or C=O, and

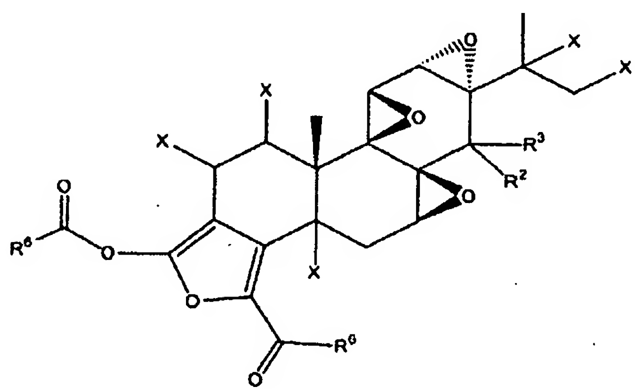
at most one of the groups X is hydroxyl, and the remaining groups X are hydrogen.

In preferred embodiments of structure **I**, CR^2R^3 is CHOH, preferably having the β-hydroxy configuration. In further embodiments, each group X is hydrogen.

Preferably, each said alkyl, alkenyl, alkynyl, alkoxy, and acyloxy moiety present in a compound of structure **I** includes at most four carbon atoms, each said cycloalkyl and cycloalkenyl moiety includes at most six carbon atoms, and each said aryl moiety is monocyclic and non-heterocyclic.

In selected embodiments of structure **I**, R^1 is alkyl, alkenyl or $C(OH)R^4R^5$, where, preferably, each of R^4 and R^5 is independently hydrogen, alkyl or alkenyl. In further embodiments, R^1 is alkyl, preferably C_1-C_3 alkyl, or hydroxyalkyl. In one embodiment, R^1 is methyl. In another embodiment, R^1 is arylacyl, preferably benzoyl ($C(O)C_6H_5$).

In a related aspect, the invention provides compounds of structure **II**:



II

where

each R^6 is independently selected from alkyl, alkenyl, alkynyl, or aryl;

CR^2R^3 is CHOH or C=O;

at most one of the groups X is hydroxyl, and the remaining groups X are hydrogen.

In preferred embodiments of structure **II**, CR^2R^3 is CHOH, preferably having the β-hydroxy configuration. In further embodiments, each group X is hydrogen.

Preferably, each said alkyl, alkenyl, and alkynyl moiety present in a compound of

structure **II** includes at most four carbon atoms, and each said aryl moiety is monocyclic and non-heterocyclic; *e.g.* substituted or unsubstituted phenyl.

In selected embodiments of structure **II**, each R^6 is aryl; preferably, each R^6 is unsubstituted phenyl.

In other aspects, the invention provides a method of effecting immunosuppression, and a method of inducing apoptosis in a cell, which is useful in antiproliferative therapy, especially anticancer therapy. The methods comprise administering to a subject in need of such treatment, or contacting said cell, respectively, with an effective amount of a compound having the structure **I** or **II** as described above. Alternatively, the invention encompasses the use of a compound of structure **I** or **II** for preparation of a medicament for effecting immunosuppression or for inducing apoptosis in a cell. The compound is typically provided in a pharmaceutically acceptable carrier. Specific embodiments of the methods and uses may employ any of the specific embodiments of formulas **I** and **II** described above.

These and other objects and features of the invention will become more fully apparent when the following detailed description of the invention is read in conjunction with the accompanying drawings.

Brief Description of the Drawings

Fig. 1 shows the cytotoxic effect in Jurkat cells of a compound of the invention, 19-methyl triptolide (designated PG795), in comparison with triptolide (designated PG490) (Example 3);

Fig. 2 shows the cytotoxic effect in Jurkat cells of a compound of the invention, 18-deoxo-19-dehydro-18-benzoyloxy-19-benzoyl triptolide (designated PG796), in comparison with triptolide 14-succinate (designated PG490-88), with and without pre-incubation in mouse or human serum (Example 3);

Fig. 3 shows inhibition of IL-2 production in Jurkat cells by a compound of the invention, 19-methyl triptolide (designated PG795), in comparison with triptolide (Example 4); and

Fig. 4 shows inhibition of IL-2 production in Jurkat cells by PG796, in comparison with triptolide 14-succinate, with and without pre-incubation in mouse or human serum (Example 4).

Detailed Description of the Invention

I. Definitions

"Alkyl" refers to a saturated acyclic monovalent radical containing carbon and hydrogen, which may be linear or branched. Examples of alkyl groups are methyl, ethyl, n-butyl, t-butyl, n-heptyl, and isopropyl. "Cycloalkyl" refers to a fully saturated cyclic monovalent radical containing carbon and hydrogen, which may be further substituted with alkyl. Examples of cycloalkyl groups are cyclopropyl, methyl cyclopropyl, cyclobutyl, cyclopentyl, ethylcyclopentyl, and cyclohexyl. "Lower alkyl" refers to such a group having one to six carbon atoms, preferably one to four carbon atoms.

"Alkenyl" refers to an acyclic monovalent radical containing carbon and hydrogen, which may be linear or branched, and which contains at least one carbon-carbon double bond (C=C). "Alkynyl" refers to an acyclic monovalent radical containing carbon and hydrogen, which may be linear or branched, and which contains at least one carbon-carbon triple bond (C≡C). "Lower alkenyl" or "lower alkynyl" such a group having two to six carbon atoms, preferably two to four carbon atoms.

"Acyl" refers to a radical having the form -(C=O)R, where R is alkyl (alkylacyl) or aryl (arylacyl). "Acyloxy" refers to a group having the form -O(C=O)R.

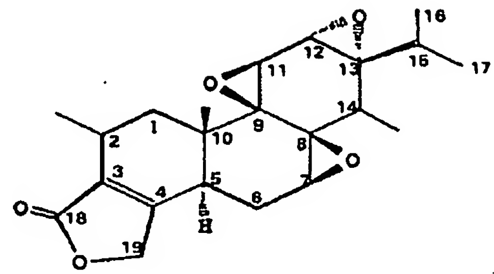
"Aryl" refers to a monovalent aromatic radical having a single ring (*e.g.*, benzene) or two condensed rings (*e.g.*, naphthyl). As used herein, aryl is preferably monocyclic and carbocyclic (non-heterocyclic), *e.g.* a benzene (phenyl) ring or substituted benzene ring. By "substituted" is meant that one or more ring hydrogens is replaced with a group such as a halogen (*e.g.* fluorine, chlorine, or bromine), lower alkyl, nitro, amino, lower alkylamino, hydroxy, lower alkoxy, or halo(lower alkyl).

"Arylalkyl" refers to an alkyl, preferably lower (C_1-C_4, more preferably C_1-C_2) alkyl, substituent which is further substituted with an aryl group; examples are benzyl and phenethyl.

A "heterocycle" refers to a non-aromatic ring, preferably a 5- to 7-membered ring, whose ring atoms are selected from the group consisting of carbon, nitrogen, oxygen and sulfur. Preferably, the ring atoms include 3 to 6 carbon atoms. Such heterocycles include, for example, pyrrolidine, piperidine, piperazine, and morpholine.

For the purposes of the current disclosure, the following numbering scheme is used

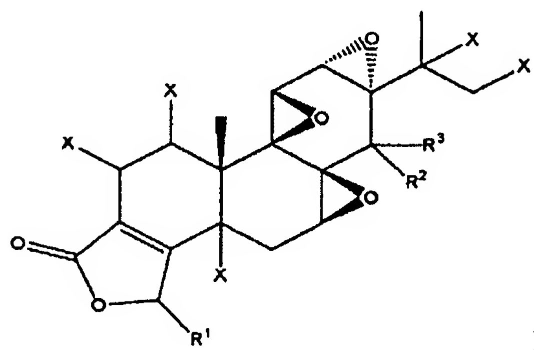
for triptolide and triptolide derivatives:



II. Triptolide Derivatives

The compounds of the invention are derivatives of triptolide or hydroxylated triptolides, resulting from alkylation or acylation of the furanoid (lactone) ring, as described below.

More specifically, the invention provides compounds represented by structure I:



I

where

R^1 is alkyl, alkenyl, alkynyl, arylalkyl, aryl, arylacyl, or $C(OH)R^4R^5$,

wherein R^4 and R^5 are independently hydrogen, alkyl, cycloalkyl, alkenyl, cycloalkenyl, any of which, excepting hydrogen, may be substituted with alkoxy, hydroxy, acyloxy, or aryl;

CR^2R^3 is CHOH or C=O, and

at most one of the groups X is hydroxyl, and the remaining groups X are hydrogen.

In preferred embodiments of structure I, CR^2R^3 is CHOH, preferably having the β-hydroxy configuration.

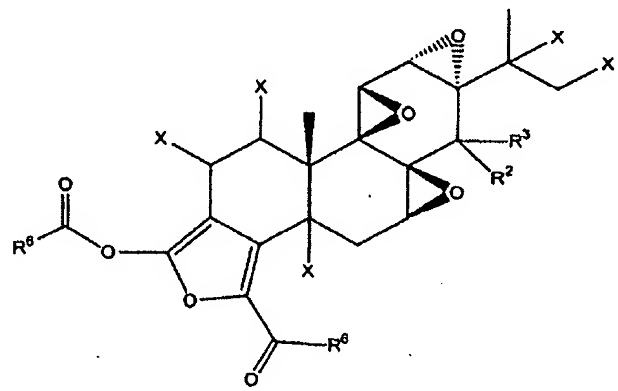
Preferably, each X is hydrogen; however, in selected embodiments, exactly one of the indicated groups X is hydroxyl. Preferred locations for hydroxyl substitution include carbons 2 and 16, as shown in the numbering scheme above.

Preferably, each said alkyl, alkenyl, alkynyl, alkoxy, and acyloxy moiety present in a

compound of structure **I** includes at most four carbon atoms, each said cycloalkyl and cycloalkenyl moiety includes at most six carbon atoms, and each said aryl moiety is monocyclic and non-heterocyclic.

In selected embodiments of structure **I**, R^1 is alkyl, alkenyl, alkynyl, arylalkyl, aryl, or $C(OH)R^4R^5$, preferably alkyl, alkenyl or $C(OH)R^4R^5$, where, preferably, each of R^4 and R^5 is independently hydrogen, alkyl or alkenyl. In further embodiments, R^1 is alkyl, preferably C_1-C_3 alkyl, or hydroxyalkyl. In one embodiment, which includes the compound designated herein as PG795, R^1 is methyl. In other embodiments, which include the compound 19-benzoyl triptolide, R^1 is arylacyl, preferably benzoyl.

In a related aspect, the invention provides compounds of structure **II**:



II

where

each R^6 is independently selected from alkyl, alkenyl, alkynyl, or aryl;

CR^2R^3 is CHOH or C=O;

at most one of the groups X is hydroxyl, and the remaining groups X are hydrogen.

In preferred embodiments of structure **II**, CR^2R^3 is CHOH, preferably having the β-hydroxy configuration. Preferably, each X is hydrogen; however, in selected embodiments, exactly one of the indicated groups X is hydroxyl. Preferred locations for hydroxyl substitution include carbons 2 and 16, as shown in the numbering scheme above.

Preferably, each said alkyl, alkenyl, and alkynyl moiety present in a compound of structure **II** includes at most four carbon atoms, and each said aryl moiety is monocyclic and non-heterocyclic; *e.g.* substituted or unsubstituted phenyl.

In selected embodiments of structure **II**, each R^6 is aryl; preferably, each R^6 is

phenyl.

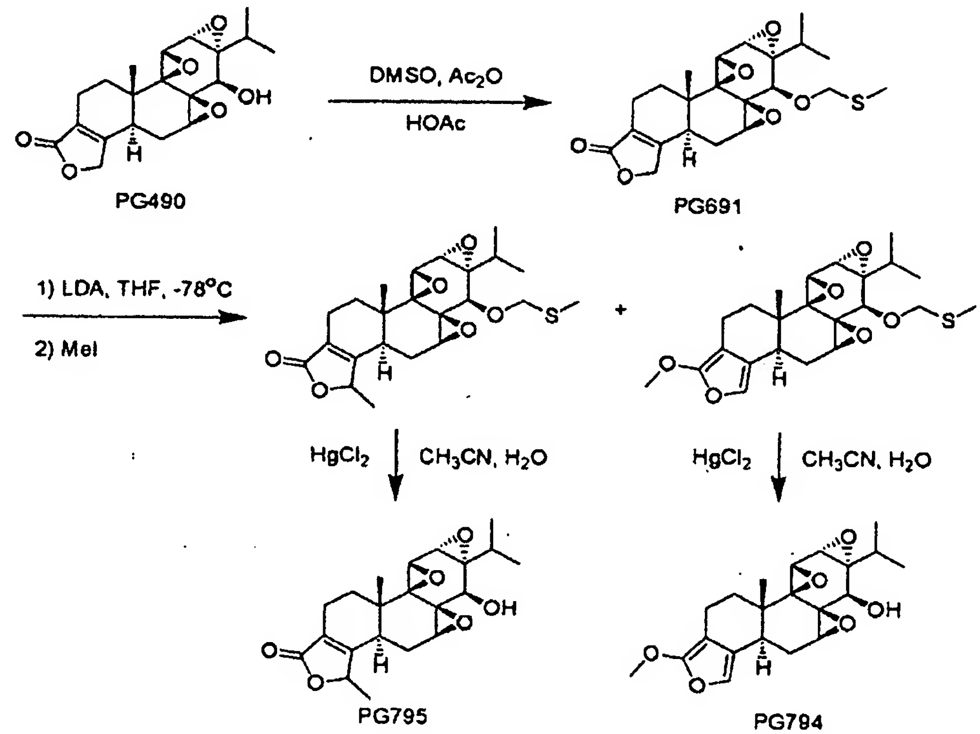
A. Preparation

The compounds of the invention may be prepared from triptolide or its hydroxylated derivatives. The latter include tripdiolide (2-hydroxy triptolide) and 16-hydroxytriptolide, which, along with triptolide, can be obtained from the root xylem of the Chinese medicinal plant *Tripterygium wilfordii* (TW) or from other known sources. The TW plant is found in the Fujian Province and other southern provinces of China; TW plant material can generally be obtained in China or through commercial sources in the United States. Methods for preparing triptolide, tripdiolide and 16-hydroxytriptolide are known in the art and are described, for example, in Kupchan *et al.* (1972, 1977); Lipsky *et al.* (1994); Pu *et al.* (1990); and Ma *et al.* (1992).

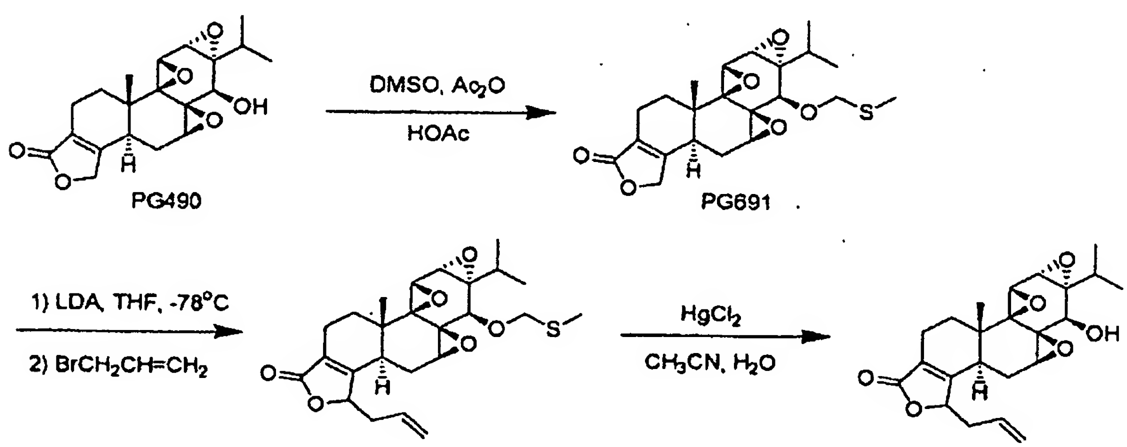
The 5-hydroxy derivative of triptolide can be prepared by selenium dioxide oxidation of triptolide, as described in co-owned U.S. provisional application serial no. 60/532,702. Briefly, in a typical preparation, a solution of triptolide and about 2.2 equivalents of selenium dioxide in dioxane is stirred at about 90°C under N_2 for 72 hrs.

Incubation of triptolide with *Cunninghamella blakesleana*, as described by L. Ning *et al.* (*Tetrahedron* 59(23):4209-4213, 2003) produces the above hydroxylated derivatives as well as 1β-hydroxytriptolide, triptolidenol (15-hydroxytriptolide), 19α-hydroxytriptolide, and 19β-hydroxytriptolide.

Compounds of formula I can be prepared by reaction of hydroxyl-protected triptolide with a strong base, such as LDA, followed by alkylation of the intermediate enolate. As shown in Scheme 1 below, where methyl iodide was used for alkylation, the isomeric furan alkoxide may also be formed. As described in Example 1, these compounds were isolated and separately deprotected by reaction with mercuric chloride.

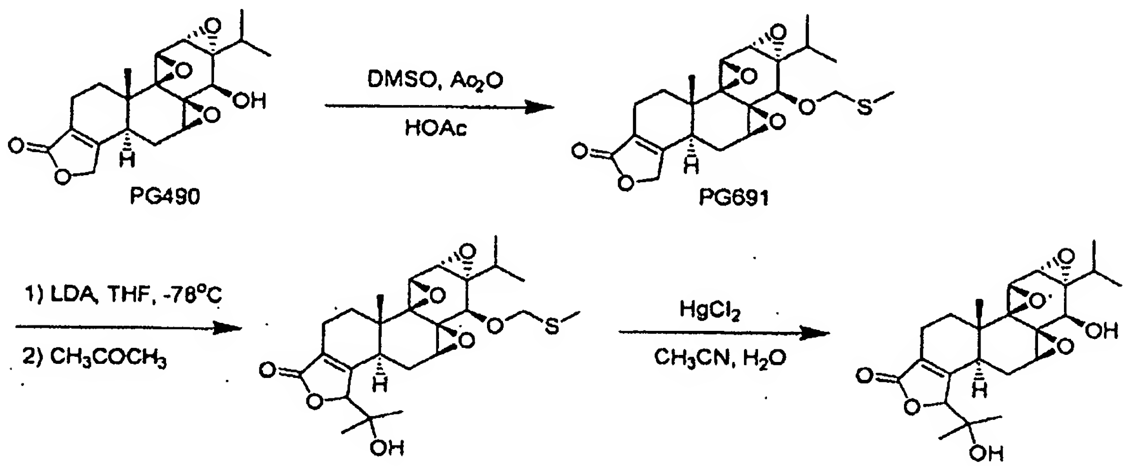


The scheme below illustrates the use of allyl bromide as alkylating agent, to give a compound of formula I in which R^1 = allyl ($-CH_2CH{=}CH_2$). Similarly, benzyl bromide was employed to give a compound of formula I in which R^1 = benzyl ($-CH_2C_6H_5$).

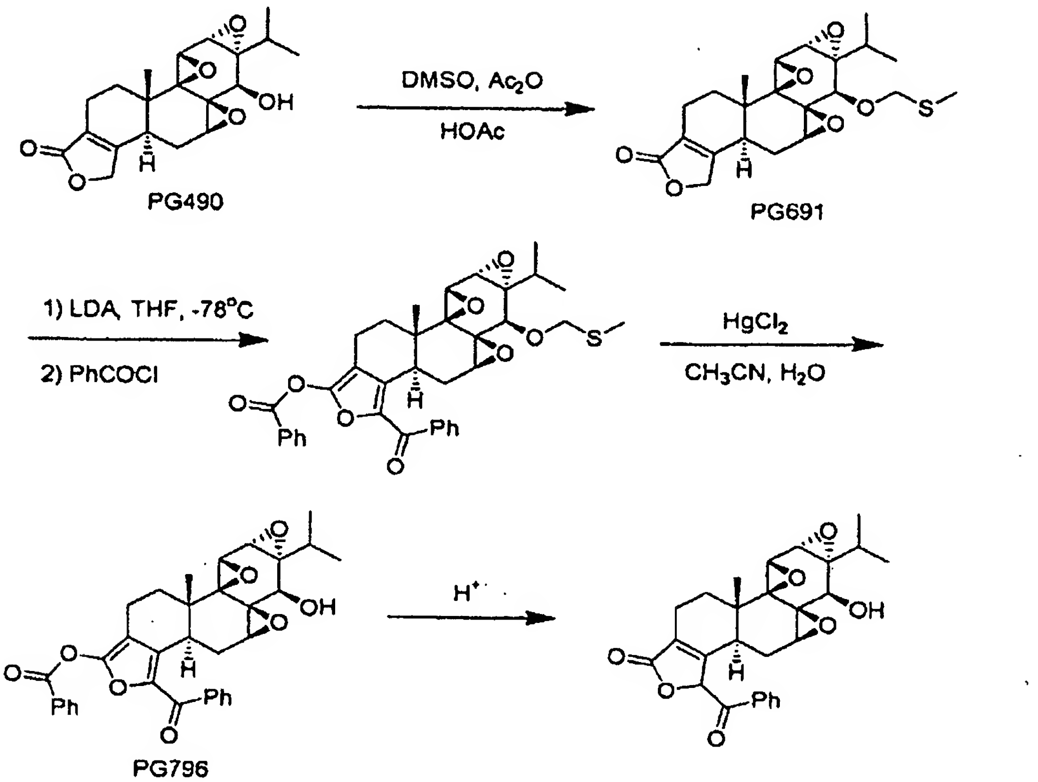


Reaction of the intermediate enolate with a ketone, as illustrated below, can be used

to generate an alcohol substituent; *i.e.* a compound of formula **I** in which R^1 is $C(OH)R^4R^5$.



Compounds of formula **II** can be prepared by reaction of the intermediate enolate with an excess of an acylating reagent, such as an acyl halide, as shown in the Scheme below. The disubstituted compound, in this case, can be hydrolyzed with aqueous acid to generate the monoderivatized conjugated enone.



B. Biological Activity

The cytotoxic activity of a compound of formula I, 19-hydroxy triptolide (designated PG795) and a compound of formula II, 18-deoxo-19-dehydro-18-benzoyloxy-19-benzoyl triptolide (designated PG796), was evaluated using a standard MTT assay, as described in Example 3. The immunosuppressive activity of these compounds was evaluated in a standard IL-2 inhibition assay, as described in Example 4. The results of these assays are shown in Figures 1-4.

PG795 showed significant activity in both assays, as shown in Figs. 1 and 3, though it was less active than triptolide (designated PG490 in the Figures).

PG796 showed a higher level of activity in both assays than the known prodrug, triptolide 14-succinate (designated PG490-88), as shown in Figs. 2 and 4. In particular, triptolide 14-succinate incubated in human serum was much less active in these assays than triptolide 14-succinate incubated in mouse serum, while PG796 showed high, and essentially equivalent, activity in both cases. (Incubation is expected to convert triptolide 14-succinate to triptolide and PG796 to the monoderivatized compound, 19-benzoyl

triptolide, shown in the above synthetic scheme.)

In addition, PG476 showed nearly equivalent activity when unincubated, suggesting that the compound is active in its original (*i.e.* non-hydrolyzed) form.

III. Therapeutic Compositions

Formulations containing the triptolide derivatives of the invention may take the form of solid, semi-solid, lyophilized powder, or liquid dosage forms, such as tablets, capsules, powders, sustained-release formulations, solutions, suspensions, emulsions, ointments, lotions, or aerosols, preferably in unit dosage forms suitable for simple administration of precise dosages. The compositions typically include a conventional pharmaceutical carrier or excipient and may additionally include other medicinal agents, carriers, or adjuvants.

Preferably, the composition will be about 0.5% to 75% by weight of a compound or compounds of the invention, with the remainder consisting of suitable pharmaceutical excipients. For oral administration, such excipients include pharmaceutical grades of mannitol, lactose, starch, magnesium stearate, sodium saccharine, talcum, cellulose, glucose, gelatin, sucrose, magnesium carbonate, and the like. If desired, the composition may also contain minor amounts of non-toxic auxiliary substances such as wetting agents, emulsifying agents, or buffers.

The composition may be administered to a subject orally, transdermally or parenterally, *e.g.*, by intravenous, subcutaneous, intraperitoneal, or intramuscular injection. For use in oral liquid preparation, the composition may be prepared as a solution, suspension, emulsion, or syrup, being supplied either in liquid form or a dried form suitable for hydration in water or normal saline. For parenteral administration, an injectable composition for parenteral administration will typically contain the triptolide derivative in a suitable intravenous solution, such as sterile physiological salt solution.

Liquid compositions can be prepared by dissolving or dispersing the triptolide derivative (about 0.5% to about 20%) and optional pharmaceutical adjuvants in a pharmaceutically acceptable carrier, such as, for example, aqueous saline, aqueous dextrose, glycerol, or ethanol, to form a solution or suspension.

The compound may also be administered by inhalation, in the form of aerosol particles, either solid or liquid, preferably of respirable size. Such particles are sufficiently small to pass through the mouth and larynx upon inhalation and into the bronchi and

alveoli of the lungs. In general, particles ranging from about 1 to 10 microns in size, and preferably less than about 5 microns in size, are respirable. Liquid compositions for inhalation comprise the active agent dispersed in an aqueous carrier, such as sterile pyrogen free saline solution or sterile pyrogen free water. If desired, the composition may be mixed with a propellant to assist in spraying the composition and forming an aerosol.

Methods for preparing such dosage forms are known or will be apparent to those skilled in the art; for example, see Remington's Pharmaceutical Sciences (19th Ed., Williams & Wilkins, 1995). The composition to be administered will contain a quantity of the selected compound in an effective amount for effecting immunosuppression in a subject or apoptosis in a targeted cell.

As described, for example, in Panchagnula *et al.* (2000), the partition coefficient or logP of a pharmaceutical agent can affect its suitability for various routes of administration, including oral bioavailability. The compounds described herein, by virtue of substitution of fluorine for one or more hydroxyl groups, are expected to have higher calculated logP values than the parent compound, triptolide, making them better candidates for oral availability.

IV. Immunomodulating and Antiinflammatory Treatment

As shown in Figs. 3-4, a compound of formula **I**, 19-methyl triptolide (designated PG795), and a compound of formula **II**, 18-deoxo-19-dehydro-18-benzoyloxy-19-benzoyl triptolide (designated PG796), inhibited IL-2 production in Jurkat cells (see Example 4) in a dose-dependent manner. The invention thus includes the use of the invention compounds as immunosuppressive agents, *e.g.* as an adjunct to transplant procedures or in treatment of autoimmune disease.

Immunoregulatory abnormalities have been shown to exist in a wide variety of autoimmune and chronic inflammatory diseases, including systemic lupus erythematosis, chronic rheumatoid arthritis, type I and II diabetes mellitus, inflammatory bowel disease, biliary cirrhosis, uveitis, multiple sclerosis and other disorders such as Crohn's disease, ulcerative colitis, bullous pemphigoid, sarcoidosis, psoriasis, ichthyosis, Graves ophthalmopathy and asthma. Although the underlying pathogenesis of each of these conditions may be quite different, they have in common the appearance of a variety of autoantibodies and self-reactive lymphocytes. Such self-reactivity may be due, in part, to

a loss of the homeostatic controls under which the normal immune system operates.

Similarly, following a bone-marrow transplant or other transplant of hematopoietic stem cells from a donor tissue source containing mature lymphocytes, the transferred lymphocytes recognize the host tissue antigens as foreign. These cells become activated and mount an attack upon the host (a graft-versus-host response) that can be life-threatening. Moreover, following an organ transplant, the host lymphocytes recognize the foreign tissue antigens of the organ graft and mount cellular and antibody-mediated immune responses (a host-versus-graft response) that lead to graft damage and rejection.

One result of an autoimmune or a rejection reaction is tissue destruction caused by inflammatory cells and the mediators they release. Anti-inflammatory agents such as NSAIDs act principally by blocking the effect or secretion of these mediators but do nothing to modify the immunologic basis of the disease. On the other hand, cytotoxic agents, such as cyclophosphamide, act in such a nonspecific fashion that both the normal and autoimmune responses are shut off. Indeed, patients treated with such nonspecific immunosuppressive agents are as likely to succumb from infection as they are from their autoimmune disease.

The compositions of the present invention are useful in applications for which triptolide and its prodrugs and other derivatives have proven effective, *e.g.* in immunosuppression therapy, as in treating an autoimmune disease, preventing transplantation rejection, or treating or preventing graft-versus-host disease (GVHD). See, for example, co-owned U.S. Patent No. 6,150,539, which is incorporated herein by reference. Triptolide and the present derivatives are also useful for treatment of other inflammatory conditions, such as traumatic inflammation, and in reducing male fertility.

The compositions are useful for inhibiting rejection of a solid organ transplant, tissue graft, or cellular transplant from an incompatible human donor, thus prolonging survival and function of the transplant, and survival of the recipient. This use would include, but not be limited to, solid organ transplants (such as heart, kidney and liver), tissue grafts (such as skin, intestine, pancreas, gonad, bone, and cartilage), and cellular transplants (such as cells from pancreas, brain and nervous tissue, muscle, skin, bone, cartilage and liver).

The compositions are also useful for inhibiting xenograft (interspecies) rejection; *i.e.* in preventing the rejection of a solid organ transplant, tissue graft, or cellular transplant

from a non-human animal, whether natural in constitution or bioengineered (genetically manipulated) to express human genes, RNA, proteins, peptides or other non-native, xenogeneic molecules, or bioengineered to lack expression of the animal's natural genes, RNA, proteins, peptides or other normally expressed molecules. The invention also includes the use of a composition as described above to prolong the survival of such a solid organ transplant, tissue graft, or cellular transplant from a non-human animal.

Also included are methods of treatment of autoimmune diseases or diseases having autoimmune manifestations, such as Addison's disease, autoimmune hemolytic anemia, autoimmune thyroiditis, Crohn's disease, diabetes (Type I), Graves' disease, Guillain-Barre syndrome, systemic lupus erythematosis (SLE), lupus nephritis, multiple sclerosis, myasthenia gravis, psoriasis, primary biliary cirrhosis, rheumatoid arthritis and uveitis, asthma, atherosclerosis, Hashimoto's thyroiditis, allergic encephalomyelitis, glomerulonephritis, and various allergies.

Further uses may include the treatment and prophylaxis of inflammatory and hyperproliferative skin diseases and cutaneous manifestations of immunologically mediated illnesses, such as psoriasis, atopic dermatitis, pemphigus, urticaria, cutaneous eosinophilias, acne, and alopecia areata; various eye diseases such as conjunctivitis, uveitis, keratitis, and sarcoidosis; inflammation of mucous and blood vessels such as gastric ulcers, vascular damage caused by ischemic diseases and thrombosis, ischemic bowel diseases, inflammatory bowel diseases, and necrotizing enterocolitis; intestinal inflammations/allergies such as Coeliac diseases and ulcerative colitis; renal diseases such as interstitial nephritis, Good-pasture's syndrome, hemolytic-uremic syndrome and diabetic nephropathy; hematopoietic diseases such as idiopathic thrombocytopenia purpura and autoimmune hemolytic anemia; skin diseases such as dermatomyositis and cutaneous T cell lymphoma; circulatory diseases such as arteriosclerosis and atherosclerosis; renal diseases such as ischemic acute renal insufficiency and chronic renal insufficiency; and Behcet's disease.

The compositions and method of the invention are also useful for the treatment of inflammatory conditions such as asthma, both intrinsic and extrinsic manifestations, for example, bronchial asthma, allergic asthma, intrinsic asthma, extrinsic asthma and dust asthma, particularly chronic or inveterate asthma (for example, late asthma and airway hyperresponsiveness). The composition and method may also be used for treatment of

other inflammatory conditions, including traumatic inflammation, inflammation in Lyme disease, chronic bronchitis (chronic infective lung disease), chronic sinusitis, sepsis associated acute respiratory distress syndrome, and pulmonary sarcoidosis. For treatment of respiratory conditions such as asthma, the composition is preferably administered via inhalation, but any conventional route of administration may be useful.

In treating an autoimmune condition, the patient is given the composition on a periodic basis, *e.g.*, 1-2 times per week, at a dosage level sufficient to reduce symptoms and improve patient comfort. For treating rheumatoid arthritis, in particular, the composition may be administered by intravenous injection or by direct injection into the affected joint. The patient may be treated at repeated intervals of at least 24 hours, over a several week period following the onset of symptoms of the disease in the patient. The dose that is administered is preferably in the range of 1-25 mg/kg patient body weight per day, with lower amounts being preferred for parenteral administration, and higher amounts being preferred for oral administration. Optimum dosages can be determined by routine experimentation according to methods known in the art.

For therapy in transplantation rejection, the method is intended particularly for the treatment of rejection of heart, kidney, liver, cellular, and bone marrow transplants, and may also be used in the treatment of GVHD. The treatment is typically initiated perioperatively, either soon before or soon after the surgical transplantation procedure, and is continued on a daily dosing regimen, for a period of at least several weeks, for treatment of acute transplantation rejection. During the treatment period, the patient may be tested periodically for immunosuppression level, *e.g.*, by a mixed lymphocyte reaction involving allogeneic lymphocytes, or by taking a biopsy of the transplanted tissue.

In addition, the composition may be administered chronically to prevent graft rejection, or in treating acute episodes of late graft rejection. As above, the dose administered is preferably 1-25 mg/kg patient body weight per day, with lower amounts being preferred for parenteral administration, and higher amounts for oral administration. The dose may be increased or decreased appropriately, depending on the response of the patient, and over the period of treatment, the ability of the patient to resist infection.

In treatment or prevention of graft-versus-host disease, resulting from transplantation into a recipient of matched or mismatched bone marrow, spleen cells, fetal tissue, cord blood, or mobilized or otherwise harvested stem cells, the dose is preferably in the range

0.25-2 mg/kg body weight/day, preferably 0.5-1 mg/kg/day, given orally or parenterally.

Also within the scope of the invention is a combination therapy comprising a compound of formula I and one or more conventional immunosuppressive agents. These immunosuppressant agents within the scope of this invention include, but are not limited to, Imurek® (azathioprine sodium), brequinar sodium, Spanidin™ (gusperimus trihydrochloride, also known as deoxyspergualin), mizoribine (also known as bredinin), Cellcept® (mycophenolate mofetil), Neoral® (Cyclosporin A; also marketed as a different formulation under the trademark Sandimmune®), Prograf™ (tacrolimus, also known as FK-506), Rapimmune® (sirolimus, also known as rapamycin), leflunomide (also known as HWA-486), Zenapax®, glucocortcoids, such as prednisolone and its derivatives, antibodies such as orthoclone (OKT3), and antithymyocyte globulins, such as thymoglobulins. The compounds are useful as potentiators when administered concurrently with another immunosuppressive drug for immunosuppressive treatments as discussed above. A conventional immunosuppressant drug, such as those above, may thus be administered in an amount substantially less (*e.g.* 20% to 50% of the standard dose) than when the compound is administered alone. Alternatively, the invention compound and immunosuppressive drug are administered in amounts such that the resultant immunosuppression is greater than what would be expected or obtained from the sum of the effects obtained with the drug and invention compound used alone. Typically, the immunosuppressive drug and potentiator are administered at regular intervals over a time period of at least 2 weeks.

The compositions of the invention may also be administered in combination with a conventional anti-inflammatory drug (or drugs), where the drug or amount of drug administered is, by itself, ineffective to induce the appropriate suppression or inhibition of inflammation.

Immunosuppressive activity of compounds *in vivo* can be evaluated by the use of established animal models known in the art. Such assays may be used to evaluate the relative effectiveness of immunosuppressive compounds and to estimate appropriate dosages for immunosuppressive treatment. These assays include, for example, a well-characterized rat model system for allografts, described by Ono and Lindsey (1969), in which a transplanted heart is attached to the abdominal great vessels of an allogeneic recipient animal, and the viability of the transplanted heart is gauged by the heart's ability

to beat in the recipient animal. A xenograft model, in which the recipient animals are of a different species, is described by Wang (1991) and Murase (1993). A model for evaluating effectiveness against GVHD involves injection of normal F1 mice with parental spleen cells; the mice develop a GVHD syndrome characterized by splenomegaly and immunosuppression (Korngold, 1978; Gleichmann, 1984). Single cell suspensions are prepared from individual spleens, and microwell cultures are established in the presence and absence of concanavalin A to assess the extent of mitogenic responsiveness.

V. Anticancer Treatment

As shown in Figs. 1-2, a compound of formula I, 19-methyl triptolide (designated PG795), and a compound of formula II, 18-deoxo-19-dehydro-18-benzoyloxy-19-benzoyl triptolide (designated PG796), were each cytotoxic to Jurkat cells (see Example 2) in a dose-dependent manner. The invention thus includes the use of the invention compounds as cytotoxic agents, particularly to treat cancers. As used herein, "cancer" refers to all types of cancer or neoplasm or malignant tumors found in mammals especially humans, including leukemias, sarcomas, carcinomas and melanoma.

The term "leukemia" refers broadly to progressive, malignant diseases of the blood-forming organs and is generally characterized by a distorted proliferation and development of leukocytes and their precursors in the blood and bone marrow. The term "sarcoma" generally refers to a tumor which is made up of a substance like the embryonic connective tissue and is generally composed of closely packed cells embedded in a fibrillar or homogeneous substance. The term "melanoma" is taken to mean a tumor arising from the melanocytic system of the skin and other organs. The term "carcinoma" refers to a malignant new growth made up of epithelial cells tending to infiltrate the surrounding tissues and give rise to metastases.

Included, for example, are cancers involving cells derived from reproductive tissue (such as Sertoli cells, germ cells, developing or more mature spermatogonia, spermatids or spermatocytes and nurse cells, germ cells and other cells of the ovary), the lymphoid or immune systems (such as Hodgkin's disease and non-Hodgkin's lymphomas), the hematopoietic system, and epithelium (such as skin, including malignant melanoma, and gastrointestinal tract), solid organs, the nervous system, *e.g.* glioma (see Y.X. Zhou *et al.*, 2002), and musculo-skeletal tissue. The compounds may be used for treatment of various

cancer cell types, including, but not limited to, brain, including medulloblastoma, head and neck, breast, colon, small cell lung, large cell lung, thyroid, testicle, bladder, prostate, liver, kidney, pancreatic, esophogeal, stomach, ovarian, cervical or lymphoma tumors. Treatment of breast, colon, lung, and prostate tumors is particularly contemplated.

The compositions may be administered to a patient afflicted with cancer and/or leukemia by any conventional route of administration, as discussed above. The method is useful to slow the growth of tumors, prevent tumor growth, induce partial regression of tumors, and induce complete regression of tumors, to the point of complete disappearance. The method is also useful in preventing the outgrowth of metastases derived from solid tumors.

The compositions of the invention may be administered as sole therapy or with other supportive or therapeutic treatments not designed to have anti-cancer effects in the subject. The method also includes administering the invention compositions in combination with one or more conventional anti-cancer drugs or biologic protein agents, where the amount of drug(s) or agent(s) is, by itself, ineffective to induce the appropriate suppression of cancer growth, in an amount effective to have the desired anti-cancer effects in the subject. Such anti-cancer drugs include actinomycin D, camptothecin, carboplatin, cisplatin, cyclophosphamide, cytosine arabinoside, daunorubicin, doxorubicin, etoposide, fludarabine, 5-fluorouracil, hydroxyurea, gemcitabine, irinotecan, methotrexate, mitomycin C, mitoxantrone, paclitaxel, taxotere, teniposide, topotecan, vinblastine, vincristine, vindesine, and vinorelbine. Anti-cancer biologic protein agents include tumor necrosis factor (TNF), TNF-related apoptosis inducing ligand (TRAIL), other TNF-related or TRAIL-related ligands and factors, interferon, interleukin-2, other interleukins, other cytokines, chemokines, and factors, antibodies to tumor-related molecules or receptors (such as anti-HER2 antibody), and agents that react with or bind to these agents (such as members of the TNF super family of receptors, other receptors, receptor antagonists, and antibodies with specificity for these agents).

Antitumor activity *in vivo* of a particular composition can be evaluated by the use of established animal models, as described, for example, in Fidler *et al.*, U.S. Patent No. 6,620,843. Clinical doses and regimens are determined in accordance with methods known to clinicians, based on factors such as severity of disease and overall condition of the patient.

VI. Other Indications

The compounds of the present invention may also be used in the treatment of certain CNS diseases. Glutamate fulfills numerous physiological functions, including an important role in the pathophysiology of various neurological and psychiatric diseases. Glutamate excitotoxicity and neurotoxicity have been implicated in hypoxia, ischemia and trauma, as well as in chronic neurodegenerative or neurometabolic diseases, Alzheimer's dementia, Huntington's disease and Parkinson's disease. In view of the reported neuroprotective effects of triptolide, particularly protection from glutamate-induced cell death (Q. He *et al.*, 2003; X. Wang *et al.*, 2003), compounds of the invention are envisioned to antagonize the neurotoxic action of glutamates and thus may be a novel therapy for such diseases.

Recent evidence from MS patients in relapse suggests an altered glutamate homeostasis in the brain. Neurotoxic events occurring in MS patients can be responsible for oligodendrocyte and neuronal cell death. Antagonizing glutamate receptor-mediated excitotoxicity by treatment with compounds of this invention may have therapeutic implications in MS patients. Other CNS diseases such as Guillain-Barre syndrome, Meniere's disease, polyneuritis, multiple neuritis, mononeuritis and radiculopathy may also be treated with the compounds of the present invention.

The compounds of the present invention may also be used in the treatment of certain lung diseases. Idiopathic pulmonary fibrosis (PF) is a progressive interstitial lung disease with no known etiology. PF is characterized by excessive deposition of intracellular matrix and collagen in the lung interstitium and gradual replacement of the alveoli by scar tissue as a result of inflammation and fibrosis. As the disease progresses, the increase in scar tissue interferes with the ability to transfer oxygen from the lungs to the bloodstream. A 14-succinimide ester of triptolide has been reported to block bleomycin-induced PF (G. Krishna *et al.*, 2001). Accordingly, the compounds of the present invention may be useful for treatment of PF. Treatment of other respiratory diseases, such as sarcoidosis, fibroid lung, and idiopathic interstitial pneumonia is also considered.

Other diseases involving the lung and envisioned to be treatable by compounds of this invention include Severe Acute Respiratory Syndrome (SARS) and acute respiratory distress syndrome (ARDS). In particular, with respect to SARS, the reduction of virus

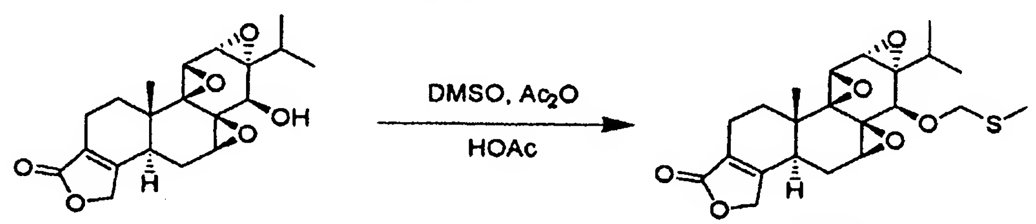
content (SARS-CoV) before the peak of the disease process and the usefulness of corticosteroid treatment, as noted below, suggest that the development of the most severe, life-threatening effects of SARS may result from the exaggerated response of the body to the infection (immune hyperactivity) rather than effects of the virus itself. (See also copending and co-owned US provisional application S.N. 60/483,335, which is incorporated herein by reference.) Corticosteroid treatment has been used in SARS patients to suppress the massive release of cytokines that may characterize the immune hyperactive phase, in the hope that it will stop the progression of pulmonary disease in the next phase. Corticosteroid treatment has produced good clinical results in reduction of some of the major symptoms of SARS. However, there are several treatment-related side effects, and there is a clear need for more selective immunosuppressive and/or antiinflammatory agents.

EXAMPLES

The following examples are intended to illustrate but not in any way limit the invention.

Example 1. Preparation of 19-Methyl Triptolide (PG795)

A. Protection of 14-hydroxyl group

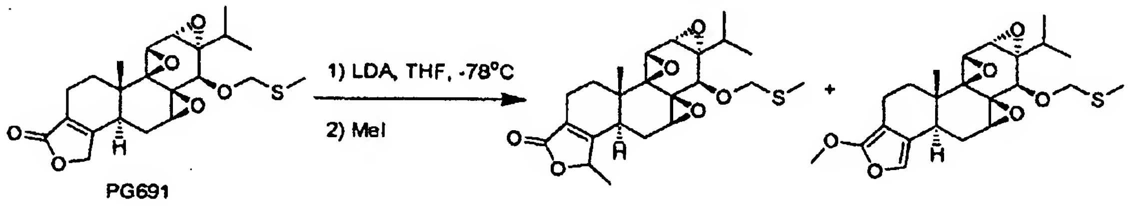


PG691

To a solution of triptolide (designated PG490) (0.56 g, 1.6 mmol) in DMSO (8.5 mL, 0.12 mol) was added acetic acid (28 mL, .49 mol) and acetic anhydride (5.6 mL, 59 mol). The clear colorless solution was stirred at room temperature for five days. The reaction mixture was poured into 200 mL of water and neutralized with solid sodium bicarbonate, added in portions. The mixture was extracted with ethyl acetate (150 mL x 3), and the extract was dried over anhydrous sodium sulfate. Concentration under reduced pressure gave the crude product as an oil. Silica gel column chromatography purification (3:2 hexanes/ethyl acetate) gave the 14-(methylthio)methoxy derivative (designated PG691)

(0.45 g, 69%) as a white foam. ^{1}H NMR ($CDCl_3$) δ 0.83 (d, J = 6.8 Hz, 3H), 1.01 (d, J = 6.8 Hz, 3H), 1.10 (s, 3H), 1.20 (m, 1H), 1.61 (m, 1H), 1.92 (dd, J = 14.7, 13.4 Hz, 1H), 2.19 (s, 3H), 2.10-2.42 (m, 4H), 2.70 (m, 1H), 3.24 (d, J = 5.5 Hz, 1H), 3.51 (d, J = 3.1 Hz, 1H), 3.68 (s, 1H), 3.79 (d, J = 3.1 Hz, 1H), 4.68 (m, 2H), 4.95 (d, J = 11.8 Hz, 1H), 5.09 (d, J = 11.8 Hz, 1H)

B. Methylation

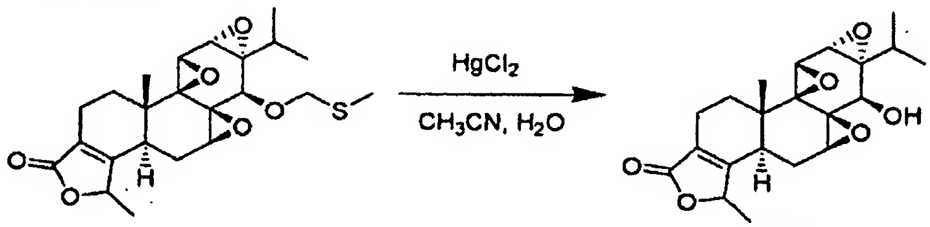


To a solution of PG691 (0.22g, 0.52 mmol) in anhydrous THF (10 mL) was added a solution of LDA in heptane/THF/ethyl benzene (0.30 mL of 2.0 M solution, 0.60 mmol) dropwise at –78 °C. The resulting solution was stirred at this temperature for 15 min, followed by the dropwise addition of methyl iodide (50 μL, 0.80 mmol). The reaction mixture was stirred at –78 °C for 2 h, then allowed to come to room temperature overnight.

The reaction mixture was neutralized with 1N HCl, and the biphasic solution was extracted with EtOAc (10 mL x 3). The EtOAc solution was washed with 5% aqueous sodium thiosulfate (10 mL x 2) and dried over anhydrous sodium sulfate. Concentration under reduce pressure gave an oil. Column purification (silica gel, 3:2 hexanes/ethyl acetate) gave two products, methylthiomethyl protected 19-methyltriptolide (45.9 mg, 20%), ^{1}H NMR ($CDCl_3$) δ 0.84 (d, J = 6.9 Hz, 3H), 1.03 (d, J = 6.9 Hz, 3H), 1.10 (s, 3H), 1.16 (m, 1H), 1.44 (d, J = 6.6 Hz, 3H), 1.59 (m, 1H), 1.92 (t, J = 14.0 Hz, 1H), 2.19 (s, 3H), 2.10-2.42 (m, 4H), 2.62 (m, 1H), 3.25 (d, J = 5.5 Hz, 1H), 3.31 (d, J = 3.1 Hz, 1H), 3.69 (s, 1H), 3.79 (d, J = 3.2 Hz, 1H), 4.89 (m, 1H), 4.95 (d, J = 11.8 Hz, 1H), 5.09 (d, J = 11.8 Hz, 1H), and methylthiomethyl protected 18-methoxyfuranotriptolide (33.1 mg, 15%), ^{1}H NMR ($CDCl_3$) δ 0.84 (d, J = 6.9 Hz, 3H), 1.01 (s, 3H), 1.02 (d, J = 6.9 Hz, 3H), 1.30 (s, 3H), 1.37 (m, 2H), 1.69 (m, 2H), 1.95 (dd, J = 15.0, 12.6 Hz, 1H), 2.10 (m, 1H), 2.19 (s, 3H), 2.27-2.47 (m, 2H), 3.19 (d, J = 5.3 Hz, 1H), 3.54 (d, J = 3.3 Hz, 1H), 3.67 (s, 1H), 3.93 (d, J = 3.3 Hz, 1H), 4.94 (d, J = 11.9 Hz, 1H), 5.08 (d, J =

11.9 Hz, 1H), 6.44 (d, $J = 2.0$ Hz, 1H).

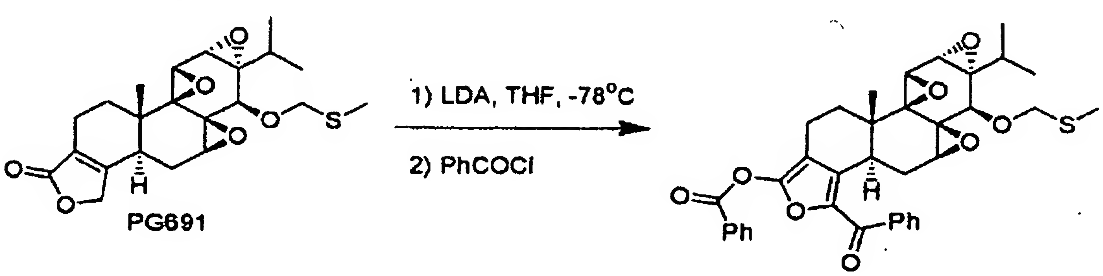
C. Deprotection



To a solution of methylthiomethyl protected 19-methyltriptolide, prepared as described above (45.9 mg, 0.106 mmol), in 1.5 mL acetonitrile/water (4:1) was added mercuric chloride (0.285 g, 1.05 mmol) in one portion. The resulting solution was stirred at room temperature overnight. The white solid which precipitated from the solution was removed by filtration through Celite® and rinsed with ethyl acetate. The EtOAc solution was washed twice with 5% aqueous NH_4OAc. The organic phase was dried (Na_2SO_4) and concentrated under reduced pressure to give the crude product. Purification by column chromatography (silica gel, 1:1 hexanes/ethyl acetate) gave the pure product (39.5 mg, 99%). ^1H NMR ($CDCl_3$) δ 0.88 (d, $J = 6.8$ Hz, 3H), 1.01 (d, $J = 6.8$ Hz, 3H), 1.11 (s, 3H), 1.16 (dt, $J = 11.5$, 2.0 Hz, 1H), 1.43 (d, $J = 6.6$ Hz, 3H), 1.54 (ddd, $J =$ 12.4, 6.4, 1.3 Hz, 1H), 1.92 (dd, $J = 14.9$, 13.4 Hz, 1H), 2.10-2.36 (m, 4H), 2.62 (m, 1H), 2.74 (d, $J = 10.8$ Hz, 1H), 3.38 (d, $J = 5.5$ Hz, 1H), 3.42 (d, $J = 10.8$ Hz, 1H), 3.53 (dd, $J = 3.1$, 0.9 Hz, 1H), 3.90 (d, $J = 3.1$ Hz, 1H), 4.88 (m, 1H); IR (CH_2Cl_2) 1754, 1047 cm^{-1}.

Example 2. Preparation of 18-deoxo-19-dehydro-18-benzoyloxy-19-benzoyl triptolide (PG796)

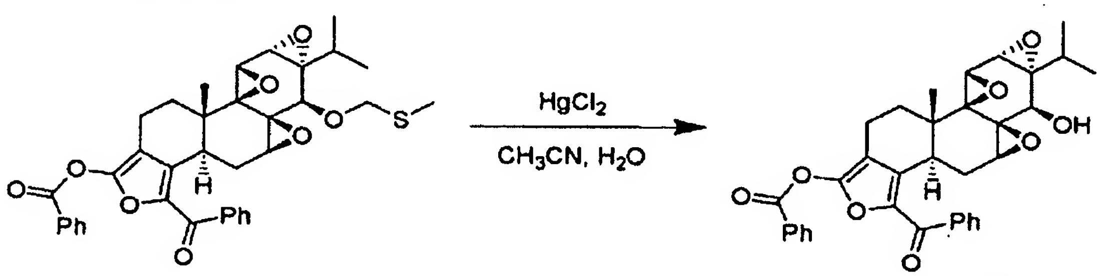
A. Acylation



To a solution of PG691, prepared as described above (73.1 mg, 0.174 mmol), in

anhydrous THF (5 mL) was added a solution of LDA in heptane/THF/ethyl benzene (0.17 mL of 2.0 M solution, 0.34 mmol) dropwise at –78 °C. The resulting solution was stirred at this temperature for 15 min, followed by the dropwise addition of neat benzoyl chloride (100 μL, 0.86 mmol). The reaction was stirred at –78 °C for 2 h. The reaction was quenched with water and the mixture was extracted with ethyl acetate (25 mL x 3). The combined organic solution was dried over anhydrous over anhydrous sodium sulfate. Concentration under reduce pressure gave an oil. Column purification (silica gel, 3:2 hexanes/ethyl acetate) gave the 14-protected product (51.2 mg, 47%). ^{1}H NMR ($CDCl_3$) δ 0.78 (d, J = 6.8 Hz, 3H), 0.91 (d, J = 6.8 Hz, 3H), 1.13 (s, 3H), 1.17 (m, 1H), 1.58 (m, 1H), 1.86 (m, 1H), 2.13 (s, 3H), 2.17-2.39 (m, 3H), 2.45 (d, J = 6.0 Hz, 1H), 2.58-2.76 (m, 2H), 3.21 (s, 1H), 3.39 (d, J = 3.1 Hz, 1H), 3.70 (d, J = 3.1 Hz, 1H), 4.85 (d, J = 11.87 Hz, 1H), 4.95 (d, J = 11.8 Hz, 1H), 7.34-7.48 (m, 3H), 7.56-7.65 (m, 2H), 7.65-7.71 (m, 1H), 7.71-7.78 (m, 2H), 8.21-8.29 (m, 2H).

B. Deprotection



PG796

To a solution of the 14-methylthiomethyl protected product, prepared as described above (51.2 mg, 0.0814 mmol), in 1.5 mL acetonitrile/water (4:1) was added mercuric chloride (0.22 g, 0.81 mmol) in one portion. The resulting solution was stirred at room temperature overnight. The white solid which precipitated from the solution was removed by filtration through Celite® and rinsed with ethyl acetate. The EtOAc solution was washed twice with 5% aqueous NH_4OAc. The organic phase was dried (Na_2SO_4) and concentrated under reduced pressure to give the crude product. Purification by column chromatography provided the pure product (32.8 mg, 71%). ^{1}H NMR ($CDCl_3$) δ 0.82 (d, J = 6.9 Hz, 3H), 0.92 (d, J = 6.9 Hz, 3H), 1.15 (s, 3H), 1.17 (m, 1H), 1.54 (m, 1H), 1.88 (m, 1H), 2.18 (septet, J = 6.9 Hz), 2.30-2.40 (m, 2H), 2.53 (d, J = 10.4 Hz, 1H), 2.56 (d, J = 7.1 Hz, 1H), 2.61 (m, 1H), 2.72 (ddd, J = 15.0, 6.4, 4.2 Hz, 2H), 2.98

(d, J = 10.2 Hz, 1H), 3.40 (d, J = 3.0 Hz, 1H), 3.81 (d, J = 3.0 Hz, 1H), 7.35-7.47 (m, 3H), 7.54-7.63 (m, 2H), 7.63-7.71 (m, 1H), 7.71-7.78 (m, 2H), 8.21-8.28 (m, 2H); IR (CH_2Cl_2) 1768, 1751, 1236, 1123 cm^{-1}.

Example 3. Cytotoxicity (MTT) Assay

Test compounds were dissolved in DMSO at a concentration of 20 mM. Further dilutions were done in RPMI1640 medium (GIBCO, Rockville, MD) supplemented with 10% Fetal Calf Serum (HyClone Laboratories, Logan, UT).

Cytotoxicity of the compounds was determined in a standard MTT assay using Cell Proliferation Kit I (#1 465 007, Roche Diagnostics, Mannheim, Germany). Briefly, human T cell lymphoma (Jurkat) cells (4 x 10^5 per well) were cultured for 24h, in 96-well tissue culture plates, in the presence of serial three-fold dilutions of test compounds or medium containing the same concentration of DMSO as in the test samples at each dilution point. The cultures were then supplemented with 10 μl/well MTT reagent for 4h and then with 0.1 ml/well solubilizing reagent for an additional 16h. Optical density at 570 nm (OD_{570}) was measured on a ThermoScan microplate reader (Molecular Devices, Menlo Park, CA).

The data is presented as OD_{570} values versus concentration of the compounds. The results for 19-methyl triptolide (PG795), compared with triptolide (PG490) and a medium control, are given in Fig. 1. The results for PG796, compared with triptolide 14-succinate (PG490-88) and a medium control, are given in Fig. 2. In this case, data is provided for both compounds incubated in human serum and in mouse serum, and for PG796 without incubation.

Example 4: IL-2 Production Assay

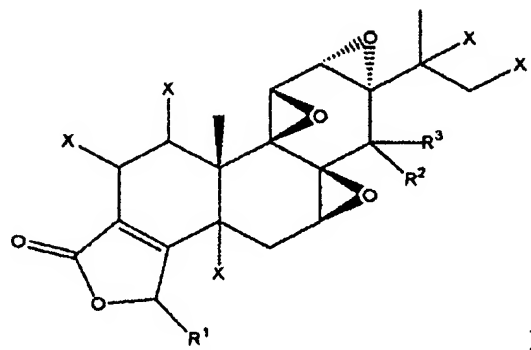
Test samples were diluted to 1 mM in complete tissue culture medium. Aliquots were placed in microculture plates that had been coated with anti-CD3 antibody (used to stimulate the production of IL-2 by Jurkat cells), and serial dilutions were prepared so that the final concentration would encompass the range of 0.001 to 10,000 nM in log increments. Cells from an exponentially expanding culture of Jurkat human T cell line (#TIB-152 obtained from American Type Culture Collection, Manassas, VA) were harvested, washed once by centrifugation, re-suspended in complete tissue culture

medium, and diluted to a concentration of 2×10^6 cells/ml. A volume of 50 μl of Jurkat cells (1×10^5 cells) was added to wells containing 100 μl of the diluted compounds, 50 μl of PMA (10 ng/ml) was added to each well, and the plates were incubated at 37°C in a 5% CO_2 incubator. After 24 hours, the plates were centrifuged to pellet the cells, 150 μl of supernatant was removed from each well, and the samples were stored at -20 °C. The stored supernatants were analyzed for human IL-2 concentration using the Luminex 100 (Luminex Corporation, Austin, TX), Luminex microspheres coupled with anti-IL-2 capture antibody, and fluorochrome-coupled anti-IL-2 detection antibody. The data were expressed as pg/ml of IL-2.

The data were plotted as the concentration of compound versus IL-2 concentration. The results for 19-methyl triptolide (PG795), compared with triptolide (PG490) and a medium control, are given in Fig. 3. The results for PG796, compared with triptolide 14-succinate (PG490-88) and a medium control, are given in Fig. 4. In this case, data is provided for both compounds incubated in human serum and in mouse serum, and for PG796 without incubation.

IT IS CLAIMED:

1. A compound having the structure **I**:



I

where

R^1 is alkyl, alkenyl, alkynyl, arylalkyl, aryl, arylacyl, or $C(OH)R^4R^5$,

wherein R^4 and R^5 are independently hydrogen, alkyl, cycloalkyl, alkenyl, cycloalkenyl, any of which, excepting hydrogen, may be substituted with alkoxy, hydroxy, acyloxy, or aryl;

CR^2R^3 is CHOH or C=O, and

at most one of the groups X is hydroxyl, and the remaining groups X are hydrogen.

2. The compound of claim 1, wherein CR^2R^3 is CHOH.

3. The compound of claim 2, wherein CR^2R^3 is CHOH(β-hydroxy).

4. The compound of claim 1, wherein each X is hydrogen.

5. The compound of claim 1, wherein each said alkyl, alkenyl, alkynyl, alkoxy, and acyloxy moiety includes at most four carbon atoms, each said cycloalkyl and cycloalkenyl moiety includes at most six carbon atoms, and each said aryl moiety is monocyclic and non-heterocyclic.

6. The compound of claim 5, wherein R^1 is alkyl, alkenyl or $C(OH)R^4R^5$.

7. The compound of claim 6, wherein R^4 and R^5 are independently hydrogen, alkyl or alkenyl.

8. The compound of claim 1, wherein R^1 is alkyl or hydroxyalkyl.

9. The compound of claim 9, wherein R^1 is C_1-C_3 alkyl or hydroxyalkyl.

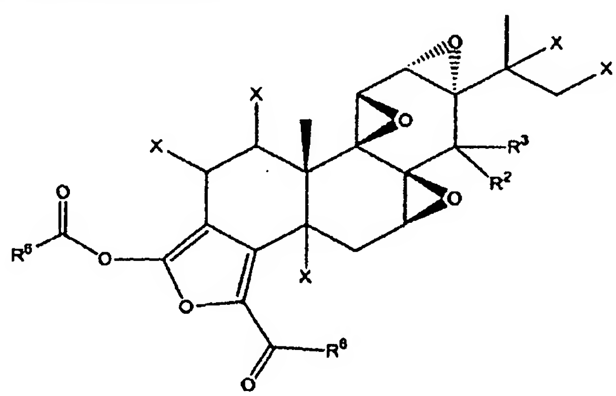
10. The compound of claim 10, wherein R^1 is methyl.

11. The compound of claim 1, wherein R^1 is arylacyl.

12. The compound of claim 11, wherein R^1 is benzoyl ($C(O)C_6H_5$).

13. The compound of claim 4, wherein R^1 is benzoyl.

14. A compound having the structure **II**:



II

where

each R^6 is independently selected from alkyl, alkenyl, alkynyl, or aryl;

CR^2R^3 is CHOH or C=O;

at most one of the groups X is hydroxyl, and the remaining groups X are hydrogen.

15. The compound of claim 14, wherein CR^2R^3 is CHOH.

16. The compound of claim 15, wherein CR^2R^3 is CHOH(β-hydroxy).

17. The compound of claim 14, wherein each X is hydrogen.

18. The compound of claim 14, wherein each said alkyl, alkenyl, and alkynyl moiety includes at most four carbon atoms, and each said aryl moiety is monocyclic and non-heterocyclic.

19. The compound of claim 14, wherein each R^6 is aryl.

20. The compound of claim 19, wherein each R^6 is phenyl.

21. A method of effecting immunosuppression, comprising administering to a subject in need of such treatment, in a pharmaceutically acceptable vehicle, an effective amount of a compound of claim 1 or claim 14.

22. A method of inducing apoptosis in a cell, comprising contacting said cell with an effective amount of a compound of claim 1 or claim 14.

ABSTRACT

Disclosed are compounds based on lactone ring modifications of triptolide and hydroxylated triptolide, for use in therapy, such as antiproliferative, anticancer, and immunosuppressive therapy.